optica

# Femtosecond phase control in high-field terahertz-driven ultrafast electron sources: supplementary material

DONGFANG ZHANG,[1,*] ARYA FALLAHI,[1] MICHAEL HEMMER,[1] HONG YE,[1] MOEIN FAKHARI,[1,2] YI HUA,[1] HUSEYIN CANKAYA,[1] ANNE-LAURE CALENDRON,[1,2] LUIS E. ZAPATA,[1] NICHOLAS H. MATLIS,[1] FRANZ X. KÄRTNER,[1,2]

[1] *Center for Free-Electron Laser Science, Deutsches Elektronen Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany*
[2] *Department of Physics and The Hamburg Centre for Ultrafast Imaging, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
**Corresponding author: dongfang.zhang@cfel.de*

*Published 11 July 2019*

**This document provides supplementary information to "Femtosecond phase control in high-field terahertz-driven ultrafast electron sources," https://doi.org/10.1364/OPTICA.6.000872.**

## S1. 5-layer STEAM-linac

Figure S1 shows the schematic of the designed 5-layer segmented structure for the STEAM-linac. It is based on the use of 2×50 μJ THz energy that gives ~ 200 keV acceleration. The thickness and length of each layer are adjusted to maintain the maximum interaction time.

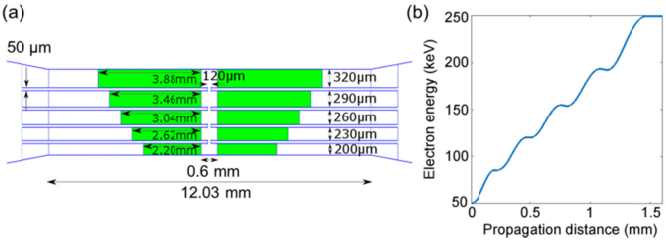


Figure S1. (a) Schematic illustration of the designed 5 layer segmented waveguide linac structure. (b) Calculated acceleration along the electron propagation direction.

## S2. Laser system

Experiments are performed with a 1.1 ps duration, 50 mJ energy, 1020 nm wavelength Yb:YLF laser operating at 10 Hz repetition rate. THz pulses with a center frequency of 0.29 THz are generated by the well-established tilted pulse-front method [1] in a $LiNbO_3$ crystal, resulting in 2 × 200 nJ pulses and 2 × 30 μJ for the STEAM-buncher and STEAM-linac respectively from the NIR laser system. Substantial losses due to beam transport and input coupling of the THz beam, however, result in pulse energies at the interaction region of 2 × 100 nJ and 2 × 15 μJ for the STEAM-buncher and STEAM-linac, respectively.

## S3. Particle-in-cell simulations

For the simulation of THz field propagation in the STEAM device, an in-house time-domain Maxwell solver based on the Discontinuous Galerkin Time Domain (DGTD) method is developed. The software is written in C++ and is efficiently parallelized using the Message Passing Interface (MPI) library. The geometry of the field STEAM device is drawn and discretized using the Gmsh (geuz.org/gmsh/) software and the DUNE library (www.dune-project.org) is utilized for mesh and grid management. The electron bunch is propagated using a particle-in-cell algorithm. The overall DGTD/PIC technique for the simulation of STEAM device is described in [2].

## References

1. J. Hebling, G. Almasi, I. Kozma, and J. Kuhl, "Velocity matching by pulse front tilting for large area THz-pulse generation," Opt. Express **10**, 1161 (2002).
2. A. Fallahi and F. Kärtner, "Field-based DGTD/PIC technique for general and stable simulation of interaction between light and electron bunches," J. Phys. B At. Mol. Opt. Phys. **47**, 234015 (2014).